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# HELICALLY POLARIZED RADIATION SOURCES DEVELOPMENT IN BUDKER INP

N. A. Vinokurov
*Budker Institute of Nuclear Physics, Novosibirsk, Russia*

For last years Budker INP designed and manufactured several insertion devices for generation of helically polarized radiation. The use of variable-polarization radiation is very attractive for many users. But, the design and manufacturing of such insertion devices is typically more complicated. The "three-dimensional" field causes problems for field calculations, magnetic measurements and beam dynamics. The necessity to change the polarization requires to satisfy the limitations on the magnetic field quality at the wide range of vertical and horizontal field values. Our magnetic systems, installed at different storage rings, are listed at tables below. In addition, the project of helical superconducting undulator for the x-ray free electron laser was developed recently.

Table 1. "Helical" electromagnetic undulators with variable polarization

| | Gap, mm | Maximum field, T | Period, mm | Total length, m |
|---|---|---|---|---|
| APS<br>(ANL, USA) | 9, vertical | 0.25 | 128 | 2.2 |
| OK-5 (Duke University, USA) | 40, diameter | 0.3 | 120 | 4×4=16 |
| SLS (PSI, Switzerland) | 19, vertical | 0.55/.12 | 212 | 4.5 |

Table 2. Hybrid elliptical motion wigglers developed and manufactured in Budker INP in collaboration with Argonne National Laboratory (USA) and Brookhaven National Laboratory (USA).

| | Gap, mm | Maximum field, T | Period, mm | Total length, m |
|---|---|---|---|---|
| NSLS<br>(BNL, USA) | 28×54 | 0.1/0.8 | 160 | 1 |
| APS<br>(ANL, USA) | 24×71 | 0.1/1 | 160 | 3 |

# SUPERCONDUCTING WAVE LENGTH SHIFTERS AND MULTIPOLE WIGGLERS DEVELOPED IN BUDKER INP

A.M.Batrakov, E.A.Bekhtenev, V.M.Borovikov, V.K.Djurba, M.G.Fedurin, V.V.Repkov, G.V.Karpov, S.V.Khruschev, G.N.Kulipanov, M.V.Kuzin, V.K.Lev, N.A.Mezentsev, V.A.Shkaruba

*Budker Institute of Nuclear Physics, SB RAS, Lavrentiev ave.11, 630090 Novosibirsk, Russia*

## *Abstract*

Several high-field superconducting wigglers (SCW) and wavelength shifters (WLS) are fabricated in Budker INP for generation of synchrotron radiation. Three-pole WLS with the magnetic field of 7.5 T are installed on LSU-CAMD and BESSY-II storage rings for shifting of radiation spectrum. WLS with the field of 10.3 T will be used for generation of slow positrons on SPring-8. The creation of 13-pole 7 T wiggler for BESSY-II and 45-pole 3.5 T wiggler for ELETTRA now is finished. The main characteristics, design features and synchrotron radiation properties of SCW and WLS created in Budker INP are presented in this article.

## 1 INTRODUCTION

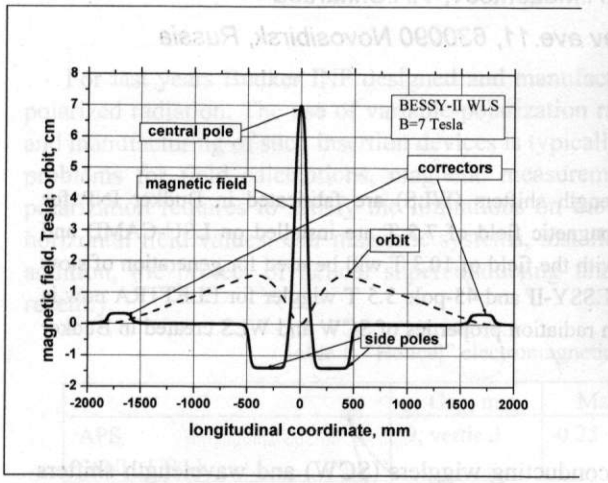
Last few years in Budker INP several high-field superconducting wigglers (SCW) and wavelength shifters (WLS) which used as insertion devices (ID) for storage rings are developed and fabricated for generation of synchrotron radiation (SR). Such devices are used for shifting of photon critical energy to the hard X-ray range due to high magnetic field and for magnification of photon flux by using of many poles. This gives new possibilities for the existing SR sources and allows to conduct new experiments. In addition this ID can be used to control the emittance of storage ring, decrease the polarization time of electron or positron beam and others. In the Table 1 the main features of SCW and WLS which are produced by Budker INP are presented.

## 2 MAGNETIC SYSTEM

Such devices as SCW and WLS are not the main elements of the storage ring lattice and do not reduce reliability of the machine. The compensation of the wiggler effects on beam dynamic has to be performed. One of the main demands for the wiggler field distribution is the minimization of the field integrals along the ID for closing of the beam orbit. Only the central pole of three-pole PLS-WLS [1] has high-field level of 7.5 T and used for generation of SR. Two side poles with low-level field of 1.5 T are needed for closing of the beam orbit. The side pole field level is selected as low as possible for spectral separation of SR from the central and the side poles to reduce contribution of the so-called “second source”.

Some inconvenience of using of three-pole wiggler is deviation of the equilibrium electron orbit and shifting of the radiation point at the different field level. Therefore for the next three-pole 7.5 T WLS (CAMD-WLS [2], BAM-WLS [3] and PSF-WLS) two additional usual steering magnets were placed at the both ends of the ID straight section for compensation of the orbit deviation. In this case the geometry of the SR experiments is not changed at any field level since the radiation point is fixed in the center of WLS. The distribution of magnetic field and electron beam orbit along BAM-WLS straight section is presented in Fig.1.

The three-pole wiggler magnetic system (see Fig.2) consists of two halves of an iron yoke with three superconducting dipoles which are located above and below of the vacuum chamber. The iron yoke is designed so that whole magnetic flux is closed inside of the magnet and there are no stray magnetic fields outside of wiggler. The key element of three-pole wigglers is high-field superconducting racetrack central pole with the iron core. The coils are reeled up from superconducting Nb-Ti wire with diameter of 0.85 mm and impregnated with epoxy compound. The critical current of used wire is equal to 360 A at a field of 7 T. Each of the central coils is separated into two sections to optimize field – current relationship and reach the maximum field. To feed the coils two independent power supplies are used. The inner and outer sections of the central coils and all side coils are powered by the first power supply with the current of ~150 A. The second power supply with the current of ~100 A feeds the outer section of the central coils. In this way the currents are summarized at the outer sections and the value of current is equal to ~250 A. Thus each section is energized by the optimal current and there is a possibility of easy control of first field integral to zero at any field levels. The magnetic field homogeneity of 10-4 at 7 T is obtained at the central pole as a result of shimming in the aperture of the magnet by special iron plates. For bandaging of superconducting winding inside of the iron yoke it is used two pairs of wedges produced from material with low heat extension factor (e.g. invar). Different thermal contraction of the used material makes it possible to compress the superconducting winding during cooling down to the liquid helium temperature. Such design makes it enable to achieve the maximum current about of 90% of short sample current.



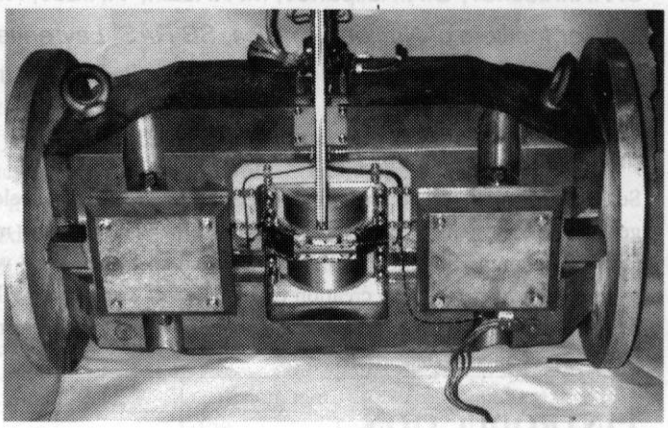


Fig.1 The distribution of magnetic field and electron beam orbit along BAM-WLS straight section

Fig.2 Magnetic system of three-pole BAM-WLS

The installation wiggler with the field of about 10T on Spring-8 with the electron beam energy of 8 GeV makes it possible to create slow positron source of high brightness [4]. To obtain magnetic fields higher than 8 T it needed to use a Nb3Sn superconducting wire with a higher critical current. The technology of manufacturing of high-field superconducting Nb3Sn windings of the racetrack type was developed and tested successfully. A rectangular Nb3Sn tie 1.45× 0.85 mm2 in size was used for manufacturing of the inner section of the central pole for the 10 T wiggler for SPring-8. For protection of Nb3Sn wire from the degradation during the quench the current distribution inside of the coils is matched so that two outer Nb-Ti sections are closer to the critical condition than the inner Nb3Sn section. In 2000 the wiggler was assembled and tested at the Spring-8 site and the maximum field of 10.3 T was achieved.

The photon flux generated by wigglers is proportional to the number of the wiggler poles. So the multi-pole wigglers are used for enhancement of the X-ray flux. Multi-pole 7 T wiggler with 13 poles and 3.5 T one with 45 poles are produced now by Budker INP for HMI-BESSY and ELETTRA, correspondingly. In 2001 the short prototypes of this wiggler with three central poles and four side poles used for orbit compensation were successively tested. The maximum fields of 7.6 T on magnetic gap of 19 mm was obtained for HMI-BESSY prototype. For ELETTRA prototype the maximum field of 3.7 T on 16.5 mm magnetic gap was achieved. The full-size multi-pole wigglers mentioned above will be finished and installed on the storage rings in 2002.

## 3 CRYOGENIC SYSTEM

The superconducting magnets are inserted into a special liquid helium cryostat. In the first cryostat for PLS-WLS with liquid helium consumption of 3 liter per hour there was only one cooper thermal screen cooled by liquid nitrogen. A whole series of improvements was carried out for reduction of liquid helium consumption. The view of other cryostats for BESSY-WLS and Spring-8 where heat inleakage into the helium vessel from outside is minimized using special cooling machines are shown in Fig.3 and Fig.4.

The liquid helium vessel is surrounded by two screens to reduce the heat flux into helium volume. The outer and inner screens are wrapped by 30 and 10 layers of super-insulation, respectively. The screens with the temperature of 60 K and 20 K are cooled by two-stage cooling machine with the cooling power on the stages of 115 Watt and 15 Watt, respectively. There is vacuum insulation with the value of $10^{-7}$ Torr between the helium vessel and an external warm stainless vessel. This insulating vacuum of the cryostat is independent and completely separated from the vacuum system of the storage ring. The special cevlar suspensions are used for hanging of the helium vessel and the screens to minimize heat inleakage. The ends of the suspensions pass through the external vessel walls and are used for precise alignment of the magnet position. Two pairs of HTSC ceramic current leads connected with the optimized cooper current leads are used to energize the magnet coils. The using of ceramic current leads permits to decrease heat inleakage 5 times less compare with optimized cooper current leads. Heat flux coming along the current leads from the upper flange due to thermal conductivity is taken off by connecting of cooper current leads to the cooler stages through the special ceramic contact. After energizing the magnet coils are closed by persistent current superconducting switch and wiggler go into "freezing current" operation mode.

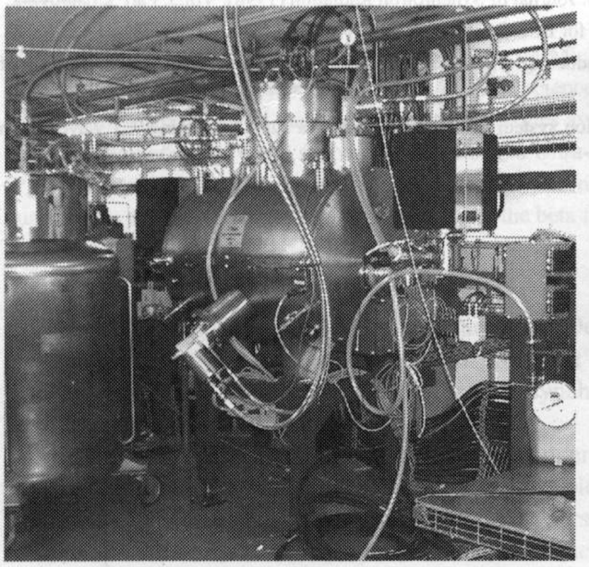


Fig.3 View of 7 Tesla BAM-WLS on BESSY-II storage ring

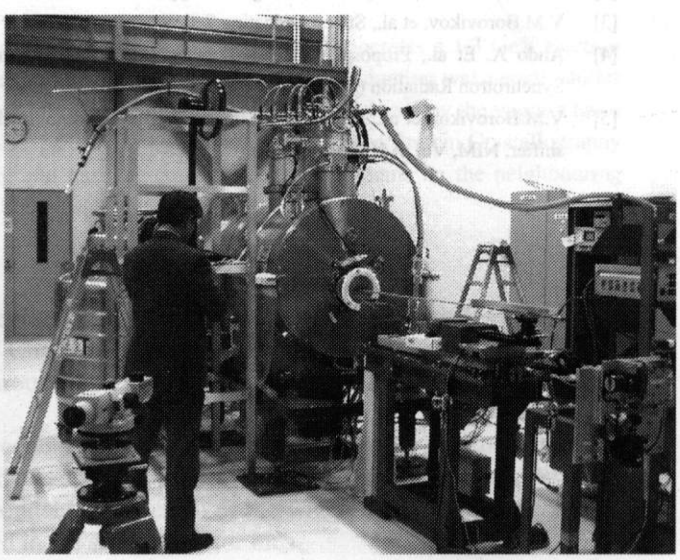


Fig.4 View of 10 Tesla WLS on Spring-8 storage ring

Table 1. Main parameters of SCW and WLS produced in BINP

| | Magnetic field, T Max/normal | Number of poles | Pole gap mm | Main Pole length mm | Magnetic length mm | Vertical aperture mm | Radiation power kWatt |
|---|---|---|---|---|---|---|---|
| PLS-WLS<br>(Korea), 1995 | 7.68<br>(7.5) | 1+2 | 48 | 170 | 800 | 26 | 3.6 |
| CAMD-WLS<br>(USA), 1998 | 7.55<br>(7.0) | 1+2 | 51 | 172 | 972 | 32 | 5.3 |
| SPring-8<br>(Japan), 2000 | 10.3<br>(10.0) | 1+2 | 40 | 200 | 1042 | 20 | 100 |
| BESSY-WLS<br>(Germany),2000 | 7.5<br>(7.0) | 1+2 | 52 | 172 | 972 | 32 | 13 |
| BESSY-PSF<br>(Germany),2001 | 7.5<br>(7.0) | 1+2 | 52 | 172 | 972 | 32 | 13 |
| BESSY-HMI<br>(Germany),2002 | 7.67<br>(7.0) | 13+4 | 19 | 74 | 1360 | 14 | 60 |
| ELETTRA<br>(Italy), 2002 | 3.7<br>(3.5) | 45+4 | 16.5 | 32 | 1680 | 11 | 8.8 |

Then a special system controlled by computer makes mechanical disconnection of cooper current leads from HTSC ones inside of the cryostat. The consumption of the liquid helium at the mode of disconnected current leads is equal to 0.12 liters per hour. It enables to refill liquid helium in the cryostat not often then 1 time per month. To compensate the current decay in the "freezing current" mode the magnetic field is stabilized with accuracy of $10^{-4}$ at 7 Tesla by feedback system with using of NMR probes and special transformers called magnetic flux pumps [5]. To decrease the current decay a special welding technique was developed for decreasing of contact resistance between the superconducting coils.

## 4 CONCLUSION

Budker INP actively develops manufacturing of high-field superconducting wigglers and wavelength shifters. Design of high-field wigglers has much in common. However, these wigglers don't repeat each other but have their own distinctive features, defined by specific requirements.

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# 5 T NON-SUPERCONDUCTING WIGGLER

E. Antokhin, Y. Kolokolnikov, G. Kulipanov, E. Levichev, V. Mishnev,V. Panchenko , P. Piminov, P. Vobly

*Budker Institute of Nuclear Physics, Novosibirsk, Russia.*

## *Abstract*

At present at Budker Institute of Nuclear Physics the non-superconducting three pole wiggler is developed. The wiggler provides 5 T magnetic field in 20 mm pole gap with using permanent magnets and coils. Magnet design of the wiggler, its effect on electron beam dynamics of storage ring VEPP-3 and spectra of synchrotron radiation are described in given paper.

## 1 INTRODUCTION

The wiggler presents 3-pole shifter with 5 T peak field of the central pole and 1.5 T field of the side poles. Peak field provides critical energy of photons about 13 keV for 2 GeV electron beam energy of storage ring VEPP-3. The maximum field of 5 T is achieved by using combination of electrical copper coils and permanent magnets located on the central pole. Such combination allows to change field in wide range from less than 1 kGs up to 50 kGs with acceptable influence on electron beam dynamics.

## 2 MAGNET DESIGN

Picture of the wiggler is shown in Fig.1. The central pole is surrounded by blocks of permanent magnets and copper coils. The central pole has taper shape in longitudinal and transverse directions. In longitudinal direction the pole edges lie on line going under 45° with respect to the center of the wiggler. Such a form of the central pole allows to achieve maximum contribution to field on wiggler axis from the pole steel, which is under strong saturation. The central pole is made of Permendur material with high level of saturation induction, that does increase the peak field. The copper coil has rectangular cross-section and is designed of copper bus with cooling channel. Its configuration and location are optimized in order to have maximum contribution to on-axis field and to facilitate fabrication. Permanent magnet blocks are located on the nearest position to the center of the wiggler so that to achieve their maximum contribution to the peak field. Upper part of the permanent magnet blocks serves for decreasing saturation of the central pole. The magnetization direction of permanent magnets is parallel to horizontal plane and directed towards to the center of the wiggler. So there is no demagnetization of permanent magnet by general (vertical) component of magnetic field. The horizontal component of wiggler field does not increase $10^{-12}$ kGs and does not lead to demagnetization of modern permanent magnets. In transverse direction the central pole has width of 7 cm that is necessary to provide required homogeneity of magnetic field in that direction.

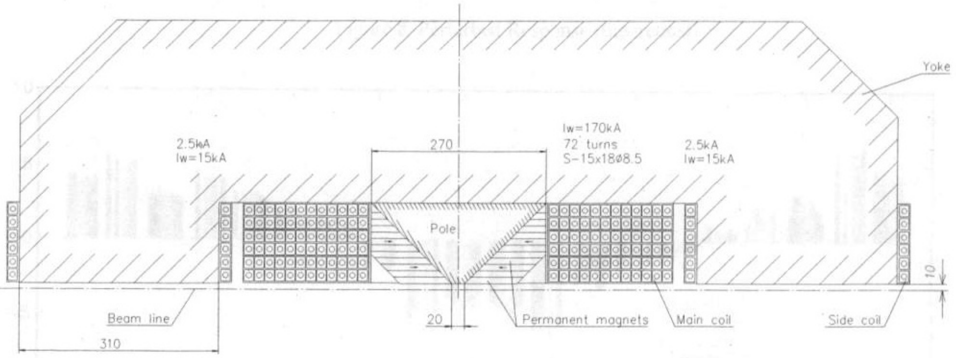

Fig. 1 Schematic view of 5 T wiggler (only upper part is shown)

Feature of this type of wigglers is residual magnetic field at zero coil current due to permanent magnets. This field has non-zero integral and can be compensated by main or side coils. At low energy of electron beam it can lead to distortion of beam optics and necessity to compensate one. In our case the residual field does not increase 1 kGs and does not influence on beam optics.

The magnetic and design parameters are given in Tables 1 and 2 correspondently. Fig.2 and 3 show the longitudinal and transverse distribution of magnetic field correspondently.

Table 1. Wiggler magnetic parameters

| | |
|---|---|
| Maximum magnetic field | 5 T |
| Pole gap | 20 mm |
| Field in side magnet yoke | 1.5 T |
| Minimum magnetic field | 0.1 T |
| Remanence field of permanent magnets | 13 kGs |
| Integral homogeneity at ± 1 cm | $5\cdot10^{-4}$ |

Table 2. Wiggler design parameters

| | |
|---|---|
| Total length | 1360 mm |
| Pole width in transverse direction | 70 mm |
| Pole width in longitudinal direction | 20 mm |
| Bus current | 2500 A |
| Number of amper-turns | 72 |
| Dimensions of copper bus: | 15×18, mm |
| Power: for 4.5 T peak field | 55 kW |
| for 5 T peak field | 100 kW |

## 3. WIGGLER INFLUENCE ON BEAM DYNAMICS

Table 3 presents the linear optics parameters of storage ring VEPP-3: original parameters, disturbed parameters due to the wiggler set up and parameters after the distortion compensation. As one can see the original and disturbed parameters differ for several percents. The distortion can be compensated by elements of the magnetic lattice according to power supply system.

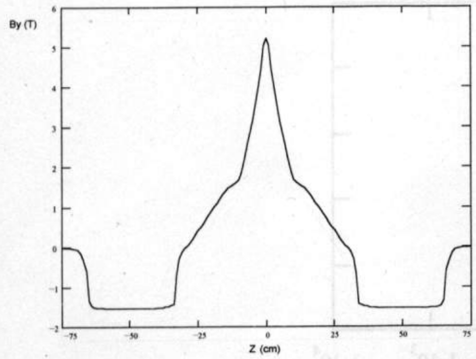

Fig. 2 Longitudinal distribution of magnetic field

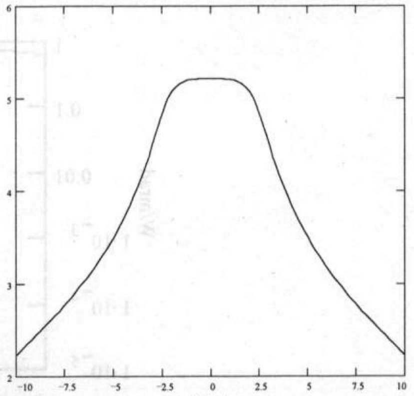

Fig. 3 Transverse distribution of magnetic field

Table 3. Linear optics parameters for storage ring VEPP-3

| | Original lattice | Disturbed lattice | Compensated lattice |
|---|---|---|---|
| $\nu_X$, | 5.146753 | 5.127541 | 5.146748 |
| $\nu_Z$, | 5.180953 | 5.196997 | 5.180948 |
| $\beta_X$, m | 3.718 | 3.57 | 3.733 |
| $\beta_Z$, m | 1.994 | 2.206 | 2.153 |
| $\alpha_X$ | 1.459 | 1.248 | 1.328 |
| $\alpha_Z$ | -0.947 | 1.061 | -1.047 |
| $\eta_X$, m | 0.847 | 0.787 | 0.848 |
| $\alpha, 10^{-2}$ | 7.337 | 7.337 | 7.233 |
| $C_X$ | -5.185 | -5.212 | -5.233 |
| $C_Z$ | -6.069 | -6.152 | -6.183 |

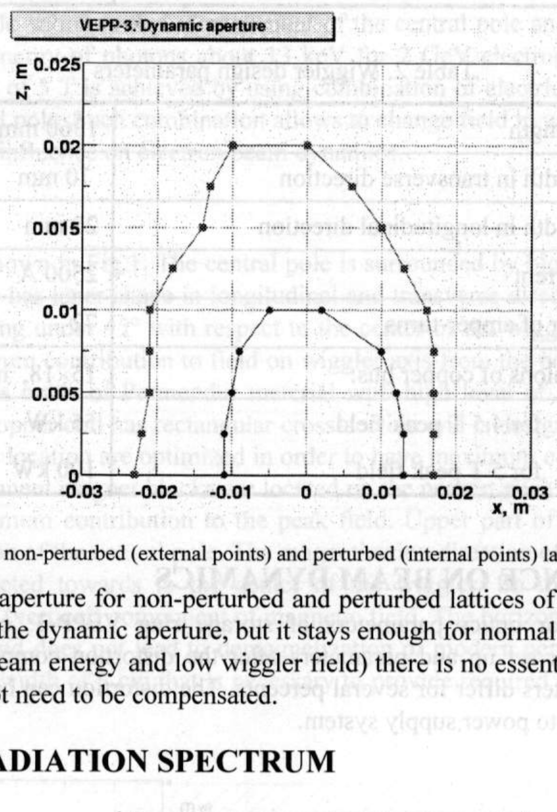

Fig. 4. Dynamic aperture for non-perturbed (external points) and perturbed (internal points) lattices of storage ring VEPP-3/

Fig. 4 shows the dynamic aperture for non-perturbed and perturbed lattices of storage ring VEPP-3. The 5 T wiggler essentially decreases the dynamic aperture, but it stays enough for normal work of machine.

At injection regime (low beam energy and low wiggler field) there is no essential wiggler influence on lattice parameters and optics does not need to be compensated.

## 4 SYNCHROTRON RADIATION SPECTRUM

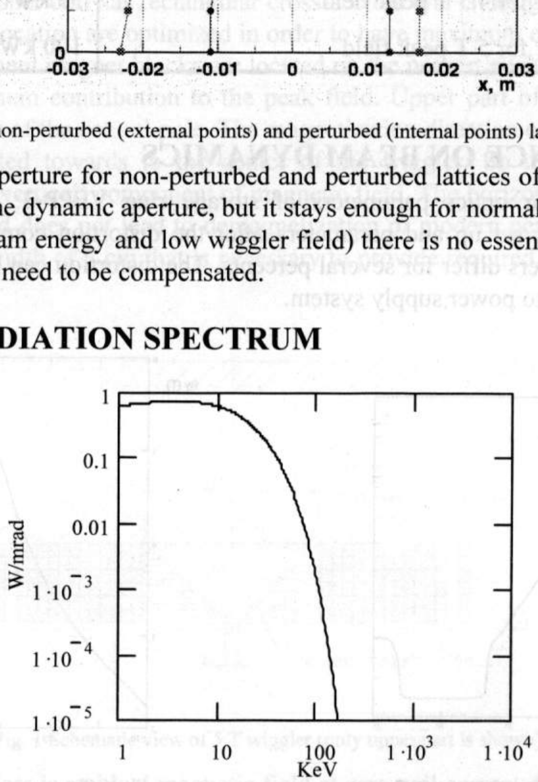

Fig. 5. The energy distribution of synchrotron radiation power integrated over vertical angle and emitted in 1 mrad of horizontal angle

The maximum 5 T magnetic field corresponds to 13 keV photon critical energy. The energy distribution of synchrotron radiation power integrated over vertical angle and emitted in 1 mrad of horizontal angle is given in Fig. 5.

The maximum SR angle from wiggler is ± 75 mrad, maximum electron beam deflection is 30 mm.

## 5 CONCLUSIONS

Creation of such type wigglers with high level of magnetic field opens new possibilities in using synchrotron radiation sources. In some cases this type wigglers can be used instead of superconducting wigglers, which are essentially expensive. Combination of copper coils and permanent magnets allows to change magnetic field (and photon critical energy) in wide range.

Such magnet design can be applied to bending magnets to form the dipole field with peak in the center of magnet and uniform field in its other parts (superbend). It will allow to have high brightness of synchrotron radiation from bending magnet and save emmitance non-perturbed.

## 6 ACKNOWLEDGES

Authors acknowledge Andrey Dubrovin – author of FEM code "MERMAID" (1). With help this code magnetic calculations of the wiggler were performed.

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